AD-A255 794

(2)

DOT/FAA/AM-92/28

Office of Aviation Medicine
Washington, D.C. 20591

Performance of Color-Dependent Tasks of Air Traffic Control Specialists as a Function of Type and Degree of Color Vision Deficiency

Henry W. Mertens
Nelda J. Milburn

Civil Aeromedical Institute
Federal Aviation Administration
Oklahoma City, Oklahoma 73125

August 1992

Final Report

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AM-92/28		

4. Title and Subtitle	5. Report Date
Performance of Color-Dependent Tasks of ATCSs as a Function of Type and Degree of Color Vision Deficiency	August 1992
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Henry W. Mertens and Nelda Milburn	
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
FAA Civil Aeromedical Institute P.O. Box 25082 Oklahoma City, OK 73125	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	
Office of Aviation Medicine Federal Aviation Administration 800 Independence Avenue, S.W. Washington, D.C. 20591	14. Sponsoring Agency Code

15. Supplementary Notes

This work was performed under task AM-C-88-90-HRR-107

16. Abstract

This experiment was conducted to expand initial efforts to validate the requirement for normal color vision in Air Traffic Control Specialist (ATCS) personnel who work at en route center, terminal, and flight service station facilities. An enlarged data base was developed involving 121 individuals with normal color vision, 31 simple and 44 extreme anomalous trichromats, and 48 dichromats; both protans and duetans were included. The performance of subjects with normal color vision was compared with the performance of individuals in various classifications of color vision deficiency on a battery of color-dependent ATCS tasks. Simulations of the ATC color tasks concerned color coding in flight progress strips (at en route centers), aircraft lights and Aviation Signal Light indicator (in tower operations), and color weather radar (at flight service stations). Errors were rare among normal trichromats. Mean errors were significantly higher at every level (degree) of color vision deficiency than in normals. Approximately 6 percent of color deficient subjects were able to perform ATC color tasks without error. The six percent were all from the simple anomalous trichromat category; all extreme anomalous trichromats and dichromats were prone to error on ATC tasks. These findings provide support for the requirement of normal color vision in initial medical screening of ATCS personnel.

17. Key Words	18. Distribution Statement
Air Traffic Controllers Color Vision Standards Performance Tests Color Vision Tests	Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	18	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGMENTS

The authors wish to acknowledge the contributions of Linda Matthews, Clara Williams, Sandra Miller, LaDonna Moore, Cynthia Fox, Jody Worley, and Chan Hellman who assisted in organization of testing, data collection and data analysis. Patsy Fowler assisted in assembly of testing materials. Many volunteers were obtained from military and civilian personnel working at Tinker Air Force Base due to the support and assistance of the offices of the Base Commander and Tinker Hospital in soliciting volunteers; we particularly thank Lt. Col. Richard Baldwin and Lt. Col. Roger Miller for their help.

PERFORMANCE OF COLOR-DEPENDENT TASKS OF AIR TRAFFIC CONTROL SPECIALISTS AS A FUNCTION OF TYPE AND DEGREE OF COLOR VISION DEFICIENCY

INTRODUCTION

Applicants for Air Traffic Control Specialist (ATCS) jobs in en route center and terminal Air Traffic Control (ATC) facilities, and Flight Service Stations (FSS) of the Federal Aviation Administration are required to have normal color vision (U.S. Government, Office of Personnel Management) because a number of ATCS tasks involve critical color-coded information and, therefore, "involve the discrimination of color for safe performance" (Adams and Tague, 1985).

The following ATCS tasks involving color-coded information were identified by job analyses (Lahey, Veres, Kuyk, Clark, and Smith, 1984a, 1984b), and used in previous research (Adams and Tague, 1985; Kuyk, Veres, Lahey, and Clark, 1986, 1987):

(1) Reading of red and black printing and red and black (or blue) handwriting on flight progress strips used by ATCSs at en route facilities.

(2) Identifying aircraft and their direction of flight at night from the ATC tower while they are in the air and on the ground, based on identification of red, green, and white navigation lights.

(3) Identifying the color of the Aviation Signal Light (ASL) indicator that gives the ATCS visual feedback concerning the signal color (red, green, or white) that is presented to direct an aircraft or ground vehicle when radio communication fails or is not available.

(4) Scanning of color weather radar displays at FSS facilities. Red, yellow, and green colors indicate different weather levels.

(5) Identifying aircraft in daytime ATC tower operations by color of aircraft or its markings.

(6) Reading of a variety of color-coded charts at all types of facilities.

(7) Selecting the appropriate colored indicator lights, keys, switches, and buttons at all types of facilities.

The flight strips, weather radar, aircraft navigation lights, and ASL indicator tasks involve color as a primary, non-redundant cue. Errors in color identification/discrimination in those tasks have the potential to place pilots, passengers, and their aircraft in danger. Tasks 5 through 7 typically involve color coding as a redundant cue of secondary importance, with primary cues such as symbol/object position, shape, and alphanumerics conveying the same information. Impaired color discrimination would be most likely to affect efficiency of performance, rather than accuracy in tasks 5 through 7. Decreased efficiency in time-limited situations, however, has the potential to lead to error.

Previous research by Adams and Tague (1985) found that a group with severe red-green color vision deficiency, protanopia, made errors on simulated ATCS color tasks, but individuals with normal color vision made no errors. Kuyk, Veres, Lahey, and Clark (1986, 1987) showed similar deficits in performance of simulated ATCS color tasks by individuals with moderate and severe levels of red-green deficiency. These studies were consistent in finding inaccurate ATCS color task performance by color deficients and, therefore, suggest the need for an ATCS color vision standard.

Additional research was performed by Mertens (1990) to determine the relation of errors in performance of simulated ATCS color tasks to type and degree of color vision deficiency in order to determine the level of color vision ability required in ATCS personnel. Mertens studied 37 normal trichromats and 71 individuals with red-green color vision deficiency of both protan and deutan types and varying degree of deficiency, as assessed

by anomaloscope testing. Simulations of ATC color tasks concerned color coding in flight progress strips used at en route centers, the Aviation Signal Light indicator light, and aircraft lights as pertinent to tower operations, and a simulation of an FSS task concerned color weather radar. These tasks were selected for study because of their frequent and consistent involvement of color as a primary task cue in safety-critical air traffic control situations. The simulations all involved the actual color materials from the ATCS tasks, or used materials with characteristics determined to be equivalent through colorimetric measurements. Errors were rare among normal trichromats in simulated normal operating conditions. Error frequency in the simulated ATC and FSS tasks was significantly higher among simple anomalous trichromats, and those with more severe deficiencies. These data add support for the requirement of normal color vision in ATCS personnel.

The present research replicated Mertens' earlier study (1990) to increase the number of subjects in all color vision diagnostic categories and enhance the data base supporting the color vision requirements for ATCS personnel. Data from the earlier and present studies were combined for the present analysis.

METHOD AND MATERIALS

Subjects

The prior experiment (Mertens, 1990), called Experiment I, involved 108 subjects, and the present experiment, called Experiment II, involved 136 subjects. Age and sex of subjects in both experiments are shown in Table 1 and Table 2 (Appendix A-1), respectively, as a function of normal and abnormal color vision. All subjects had at least 20/30 visual acuity in both near and distant vision as determined with the OPTEC 2000 vision tester or the Bausch and Lomb Orthorater. Subjects with normal color vision and color vision deficiency were solicited through advertisements in newsletters at Tinker Air Force Base and local newspapers in the Oklahoma City metropolitan area. All subjects were paid an hourly wage.

Diagnostic Color Vision Tests

The principal diagnostic instrument was the Nagel Type I anomaloscope (Schmidt-Haensch). The anomaloscope is recommended by the NRC-NAS Committee on Vision (1981) as the best instrument for diagnosis and differentiation of (1) normal trichromats from individuals with "red-green" color vision deficiencies, (2) protan and deutan types among the red-green deficients, and (3) degree of deficiency (i.e. simple anomalous, extreme anomalous, and dichromats, in order of increasing severity). Other tests were given to detect and diagnose the rare "blue-yellow" deficiencies that the Nagel anomaloscope does not detect.

The anomaloscope testing procedure described by Steen, Collins, and Lewis, (1974) was used to obtain matches for both "neutral" and "chromatic" adaptation conditions. The anomaloscope diagnostic classification procedure used is similar to that described and recommended by the NRC-NAS Committee on Vision (1981). The procedure described by the Committee on Vision bases diagnosis primarily on measurements obtained under chromatic adaptation (i.e., matches obtained after looking at the anomaloscope stimulus for at least 20 s). The anomaloscope classifications and anomaloscope classification criteria are listed in ascending order of severity; the total number of subjects in both experiments is listed for each category:

Normal Trichromats (n=121). These individuals comprise the majority of normal trichromats and have a high level of color discrimination ability. In summary, all normal trichromats had matches that fell between 33 and 50 on the anomaloscope scale and had a range less than 15 scale units. The normal trichromats included 3 subcategories. The "true" normal category included individuals whose matching range midpoint on the anomaloscope was within plus or minus 2 standard deviations (SD=2.0) of the mean midpoint (mean=40.8) for normal trichromats and whose matching range was less than or equal to 10 units. Two other sub-classes contained those normal trichromats called "deviant normal trichromats" and "weak normal trichromats" (Pokorny, Smith, Verriest, and Pinckers, 1979). These subgroups of normal trichromats may be thought of as

representing the "tails" of either the distribution for (1) the matching range size (the "weak" normal trichromats), or (2) the distribution for matching range midpoint (the "deviant" normal trichromats). Deviant color normals include normal trichromats whose midmatching point is displaced more than 2 SD, but no more than 3 SD from the mean of normal trichromats, with a matching range less than or equal to 10 units. Weak color normals include normal trichromats whose midmatching point is no more than 3 SD from the mean of normal trichromats, but whose matching range was between 10 and 15 units on the anomaloscope scale.

Simple Anomalous Trichromats (n=31). The simple anomalous trichromats are the "mildest" of inherited red-green color vision deficiencies. They were separated into simple protanomalous and simple deuteranomalous trichromats. The simple anomalous trichromats may have impairment of color discrimination ability ranging from mild to moderate. The simple anomalous trichromat categories include (1) individuals whose midmatching point falls more than 3 SD above or below the mean for normal trichromats, and whose matching range does not overlap the range of mean matches of normals, and (2) all individuals with a matching range greater than 15, but less than 26 scale units, even if their range of matches overlaps the means for normals. Those simple anomalous trichromats having a mean of matches above the mean for normal trichromats were classified as simple protanomalous, and those with a mean of matches falling below the normal mean were classified as simple deuteranomalous trichromats.

Extreme Anomalous Trichromats (n=44). These color deficients typically have severe color vision impairment and were separated into extreme protanomalous and extreme deuteranomalous trichromats categories. The extreme anomalous individuals accept a wide range of matches, overlapping both the range of matches accepted by normal trichromats and the simple anomalous trichromat. The extreme anomalous trichromats were distinguished by having a matching range greater than 25 and less than 73 scale units that frequently included the mean of normal matches as well as part of the simple deuteranomalous or protanomalous matching ranges. The extreme protanomalous typically had a midpoint of matches above the normal mean, and had reduced sensitivity to long (red) wavelengths of light. Deuteranomalous individuals typically had a matching midpoint below the mean of normals, and no evidence of a sensitivity loss to long wavelengths of light.

Dichromats (n=48). Dichromats were separated into protan and deutan groups called protanopes and deuteranopes, respectively. Dichromats have severe color deficiencies. Both protanopes and deuteranopes have a range of 73 scale units, (i.e. they accept the entire range of possible matches on the anomaloscope). Protanopes are differentiated from deuteranopes by reduced sensitivity to long wavelengths.

Several other tests were used to obtain additional diagnostic information to screen for tritan deficiencies, although none were found. The Farnsworth Dichotomous Test for Color Blindness Panel D-15 provided information to support differentiation between red-green (protan and deutan) and tritan types, along with the Farnsworth F2 Plate and AOC-HRR pseudo-isochromatic plates test. These tests have been described by others (NRC-NAS Committee on Vision, 1981; Pokorny, Smith, Verriest, and Pinckers, 1979).

ATCS Color Tasks

Flight Progress Strip (FPS) Test. The FPS test was similar to tests used in previous research by Adams and Tague (1985). It required identification of colors in color-coded computer printing or hand-writing on FPSs as used at en route centers. Subjects responded by identifying the color of computer printing (103 items) and hand writing (76 items) as red or black (blue). Since blue is permitted to be used instead of black, a small number of blue items was included. FPS materials were obtained from the Ft. Worth (Texas) en route center. There was no time limit for responding and performance was assessed in terms of number of errors and a pass-fail score. In the latter case, the failure criterion was any error. The incident illumination level was 59 lux, which corresponded to the average workstation illumination measured at the Ft. Worth en route center.

Flight Progress Strip Test - Low Illumination (FPS-L). This test utilized a subset of 38 of the hand-written items from the above test that were presented a second time under a lower, 14 lux incident illumination level. In subsequent discussion, data concerning testing at the normal 59 lux level with these items are referred to as the FPS-N test. The low illumination level was selected to be marginal for normals based on preliminary measurements, but was slightly higher than the lowest level (8.4 lux) found at an en route center that was reported by Adams and Tague (1985). There was no time limit for responding, and performance was assessed in terms of total errors and a pass-fail score; the failure criterion for the latter score was any error.

Color Weather Radar Test - Large Targets (Radar-L). This test involved identification of 7 colors including the 6 colors of the FAA weather radar color code that represent 6 different levels of precipitation, and "black," representing background or no precipitation detected. The weather radar color code involves 2 shades each of red, yellow, and green. The characteristics of display colors, 1931 CIE chromaticity coordinates x and y and luminance (L=candelas per square meter), were: (i) light green, x=.308, y=.574, L=48.3; (ii) dark green, x=.314, y=.563, L=25.5; (iii) light yellow, x=.420, y=.495, L=65.3; (iv) dark yellow, x=.423, y=.488, L=34.3; (v) light red, x=.598, y=.357, L=18.6; (vi) dark red, x=.575, y=.361, L=11.0; and (vii) black, x=.385, y=.402, L=2.6. These display color measurements were made with the same ambient illumination that was used during testing. The display colors and the 118 lux ambient illumination level were similar to measurements obtained at the McAlester (Oklahoma) FSS. The display was viewed by the subject at a distance of 71 cm. On every trial, a bar showing the colors of all 6 precipitation levels in order of magnitude was presented 7 degrees above the center of the target. Each color segment in the bar subtended 0.5 degree vertically and 1.3 degrees horizontally. The radar task required identifying the color of a 0.5 degree square target that was located at the center of a 4 degree square background. All possible combinations of target/background colors were used to discourage guessing, but only the 12 combinations most commonly found in radar and which involve adjacent precipitation levels, were used for test trials and scored. There was no time limit for responding. Following a response, there was a 5-s delay before presentation of the next stimulus. Any error caused failure of the test. Total errors were also counted.

Color Weather Radar Test - Small Targets (Radar-S). This task was identical to Radar-L, with the exception that targets were smaller, subtending approximately 0.1 degree. The 0.5 degree target size of Radar-L was chosen to be sufficiently large such that color discrimination in individuals with normal color vision would not be adversely affected by target size. With the 0.1 deg size, somewhat decreased discrimination ability for colors on the red-green axis would be expected. Discussions with Flight Service Specialists and meteorologists working at FAA facilities indicated that identification of the color of very small weather radar targets can be important. The 0.1 degree target size was similar to the size of small targets seen on several weather radar displays at FSS and en route centers and is approximately 4 x 4 pixels in size on the Tektronix 4125 color graphics work station used to present the weather radar tasks. The monitor, 38.3 cm on the diagonal, had a resolution of 1280 x 1024 pixels. Lahey, et al. (1984a) also selected 0.1 deg as a small target size relevant to ATCS color tasks.

Aircraft Lights Test (ALT). Ten pairs of lights simulating aircraft navigation lights were projected onto a white screen in a nearly dark room. The ambient illumination of the screen was 1.07 lux, the recommended maximum level for interior incident illumination on tower cab windows (Illumination Engineering Society, 1972). Kodak Wratten Filters 26 and 58 were mounted over small holes in slides to simulate red and green aircraft navigation lights. White navigation lights were simulated by using no filter. Intensity of lights was varied with neutral density Wratten filters to ensure that color could not be associated with brightness. Colors of simulated aircraft lights had the following approximate chromaticity coordinates: red, x=.693, y=.307; green, x=.269, y=.683; and white, x=.460, y=.417. Although this task was similar to the aircraft lights test of Adams and Tague (1985) in terms of target colors, the angular subtense of simulated aircraft lights was smaller, 1.4 min of arc, and the 2 lights of each pair were separated vertically by 21 min of arc. The target colors met current standards of the International Civil Aviation Organization (1988) for

aircraft navigation light colors. The criterion for failure of this test was any error.

Aviation Signal Light (ASL) Test. The subject identified signal colors as reflected in the indicator (bezel) on top of an ASL. Six signals were observed as the subject sighted the ASL out of a third floor, north window at the sky. The signals were regulated by an experimenter with controls shielded from the subject's view. Signals were of 5-s duration, and intervals between signals were 3 min. The ASL signal colors (red, green, and white) were presented randomly, with the restriction that each color be presented at least once during the 6 trials. This test was administered between the hours of 10:00am and 3:00pm with sky conditions varying from clear to heavily overcast. Any error constituted failure of the task.

In addition, all clinical color vision tests currently accepted by the FAA for initial color vision screening of ATCS applicants were given; those tests are described elsewhere (Mertens, 1990). A paper in preparation (Mertens and Milburn, 1992) will assess the validity of those clinical tests for prediction of accurate performance in the simulations of ATCS color tasks described above.

PROCEDURE

The simulated ATCS color tasks, diagnostic tests, and clinical screening tests were administered at 4 testing stations, each supervised by a laboratory technician. All anomaloscope testing was performed by the first author. The tests at each station took approximately 45 min to administer. The testing of each subject was performed in two, 2-hour sessions separated by a 1-hour lunch break or given on successive days. Within each session, the two 45-min testing periods were separated by a 15-min break.

RESULTS AND DISCUSSION

Diagnostic Classification of Subjects

The number of subjects in each classification of type and degree of color vision deficiency are shown for both Experiments I and II in Table 3 (Appendix A-1). Representation of all categories of red-green color vision deficiency was obtained in both experiments. In the combined data, the total number of normal trichromats is 121 and the total number of deficients is 123.

Pass/Fail Scoring of ATCS Color Task Performance

In air traffic control work, an error in one of the ATCS color tasks studied has the potential to place people and aircraft in jeopardy. The tasks were, therefore, scored on a pass/fail basis with failure contingent on the occurrence of any error for purposes of establishing a relationship between color vision diagnosis and performance of practical ATCS color tasks. This strict criterion ignores the fact that errors can be caused by a variety of reasons other than color vision, such as a momentary lapse of attention, motivation, etc. We assume, however, that the probability of such errors is the same in all individuals, both normals and deficients, regardless of color vision classification. All analyses given below utilize the combined data for Experiments I and II.

Relation of Pass/Fail Scores to Color Vision Classification

Pass/Fail Scores on Individual ATC and FSS Color Tasks. The number of subjects passing and failing is presented in Table 4 (Appendix A-2) for the 3 ATC tasks, FPS, ALT, and ASL, and for the FSS Radar-L task, as a function of type and degree of color vision deficiency. All data in this table involve simulation of normal operating situations. Errors were rare among normal trichromats. Of the 8 normal trichromats who erred, 7 erred on one task; the other made 1 error on each of two tasks, the FPS and Aircrafts Lights tasks. In contrast, many simple anomalous trichromats, extreme anomalous trichromats, and dichromats made errors in all tasks involving normal operating conditions. The deuteranomalous tended to pass more often than the protanomalous in the Radar-L task and the ASL task, but not in the FPS and Aircraft Lights tasks.

Overall Pass/Fail Scores. Table 4 also contains an overall pass/fail score for the 3 ATC tasks, FPS, ALT, and ASL. This composite score is called "ATC TASKS" in Table 4. An additional overall composite score for the 3 ATC tasks plus the FSS task, Radar-L, is named "ATC/

FSS TASKS." These overall scores were only for the normal observation conditions and did not involve the low illumination condition of the FPS-L test or the small radar target size of the Radar-S task. Any error on any task was cause for failure on an overall score. On the "ATC TASKS," 2 normal trichromats failed, and on the "ATC/FSS TASKS," 8 normal trichromats failed. Only 7 of the 123 color deficients passed the "ATC TASKS" composite, and only 6 of those 7 color deficients also passed on the "ATC/FSS TASKS" composite. The color deficient individuals who passed on both overall measures were all from the simple anomalous trichromat classifications. No individuals from the extreme anomalous or dichromat classifications passed, (i.e. none passed all 4 tasks). Of the 6 simple anomalous trichromats who passed all practical tests, 5 had an anomaloscope range less than 20 scale units and a matching range midpoint between 37.0 and 44.5. That is, their range size was moderate among anomalous trichromats, and their matching range midpoints were within the range of midpoints for normal trichromats. The sixth simple anomalous who passed all 4 practical tasks had a range of 25.0 and a midpoint of 17.5 which was outside the range of midpoints for normal trichromats. As mentioned above, a seventh simple anomalous passed the FPS, ALT, and ASL tasks, but failed the Radar-L task. The latter individual also had a small range, 10.0 units, and midpoint of 58.0, which was also outside the range midpoints for normal trichromats.

Comparison of Experiments I and II. It was apparent that a greater proportion of individuals in the simple anomalous trichromat category had error free performance of ATC and FSS practical color tasks in Experiment II than in Experiment I; that can be seen in Table 5 (Appendix A-3) in which frequency of passing and failing the ATC TASKS, and ATC/FSS TASKS composite scores are shown as a function of degree of deficiency for each experiment. A Chi-square test was used to compare the frequencies of passing and failing in Experiment I vs. Experiment II within each of the four color vision categories of Table 5 in both ATC and ATC/FSS TASKS scores. The difference between experiments was significant only for the case of simple anomalous trichromat category in both the ATC/FSS TASKS scores [x^2(df=1)=6.24, p<.02] and the ATC TASKS scores [x^2(df=1)=8.42, p<.01]. The significant difference between experiments in the number of simple anomalous trichromats who performed practical tasks without error was probably caused by the sampling of approximately 3 times the number of male normal trichromats in Experiment II, as compared to Experiment I. That resulted in finding more color deficient individuals who Pokorny, et al. (1979) referred to as "minimally affected anomalous trichromats." Members of this group are identified by the anomaloscope as simple anomalous trichromats, but they have excellent color discrimination ability as shown by their ability to consistently pass pseudo-isochromatic plate tests with known high validity for distinguishing between normal trichromats and color deficients. Four of the 6 simple anomalous trichromats who made no errors and passed the ATC/FSS TASKS score, also passed all pseudo-isochromatic plate tests given in the companion study (Mertens and Milburn, 1992), and all 4 individuals were subjects in Experiment II. Pokorny, et al. (1979) states that the minimally affected anomalous trichromats may comprise from 1 to 5 percent of the anomalous trichromatic population, which is in rough agreement with occurrence in the samples of our 2 experiments. A frequency of zero out of 23 male subjects was found in Experiment I, and 4 out of 65 males were found in Experiment II; of the total anomalous trichromats in both experiments, the 4 minimally affected comprise 5 percent of all anomalous trichromats.

In summary, the simple anomalous trichromats who were able to perform all practical tasks under normal observation conditions without error, and who could perform as well as any normal trichromat, had small or moderately small anomaloscope ranges (25 scale units or less) and 5 out of 7 had matching range midpoints that were within the range of midpoints for normal trichromats. No individual with a matching range greater than 25 was able to pass all 4 tasks presented under simulated normal observation conditions.

Effect of Marginal Viewing Conditions on Pass/Fail Scores. Performance under normal and marginal conditions on FPS-N and FPS-L flight strip tasks and the 2 radar tasks, Radar-L and Radar-S, is described in Table 6 (Appendix A-3). Under low (14 lux) illumination in the FPS-L task, 97% of normals made no errors, while

90% of anomalous trichromats and dichromats failed. In the Radar-S task, when target size was small, 69% of normal trichromats made no errors, while 96% of anomalous trichromats and dichromats did make errors. The probability of any color discrimination error is much higher among anomalous trichromats and dichromats than in normal trichromats under marginal/difficult viewing conditions as well as normal viewing conditions.

Relation of Error Scores to Color Vision Classification

Error Scores on Individual ATC and FSS Color Tasks. The total number of errors on a task comprised the error score for that task. The mean and standard deviation of error scores and 95% confidence intervals for the mean are shown for the FPS, ALT, and ASL tasks performed in normal conditions in Table 7 (Appendix A-4) as a function of degree and type of color vision deficiency. Similar data are shown in Table 8 (Appendix A-5) for both target size conditions of the radar task (Radar-L and Radar-S), and the 2 illumination conditions used with the flight strips task (FPS-N and FPS-L). The confidence intervals are presented for comparison of means for color deficient groups and normal trichromats. The low, near zero variance among normal trichromats makes analysis of variance inappropriate for comparison of the means of normals with means for deficients (Box, 1954). Error scores in all tasks increase with degree of color vision deficiency, and mean error scores for all degrees of color vision deficiency are typically significantly higher than the mean error score for normals. That is, for all tasks and categories of color vision deficiency, except the simple protanomalous in the FPS and ASL tasks, the 95 percent confidence interval for the mean of deficients does not include the mean for the normal trichromats. Similarly, the mean number of errors for simple anomalous trichromats in all tasks is typically outside the 95 percent confidence interval for groups with more severe deficiencies of the same type. While mean error scores are typically greater in dichromats than extreme anomalous trichromats, that difference is not always statistically significant. In summary, the error score data of Tables 7 and 8 again indicate, as did the pass/fail data, that the probability of error was higher among anomalous trichromats and dichromats than among normal trichromats on all 4 simulated ATCS tasks. Among those individuals with color vision deficiency, the probability of error increased with the severity of the deficiency.

Comparison of Protans and Deutans in Normal Viewing Conditions. The performance of protans and deutans was compared in analyses of error scores for each task; the data for normal conditions of the FPS, ALT, and ASL tasks are shown in Table 7. Analysis of variance was used to evaluate differences in error scores as a function of degree of color vision deficiency among protans and deutans in all tasks; normal trichromats were excluded from this analysis. The main effect of degree of color deficiency was statistically significant for all four tasks in the data summarized in Table 7. That main effect has been discussed above and will not be discussed further. Deutans made significantly fewer errors than Protans only in the FPS task [$F(1,117)=61.86$, $p<.001$]. The interaction of type of deficiency with degree of deficiency was also significant [F(20.89, $p<.001$] in the case of the FPS task. That interaction reflects the greater difference between protans and deutans among the extreme anomalous trichromats and dichromats than among the simple anomalous trichromats.

Effect of Marginal Viewing Conditions on Error Scores. The mean errors are shown for the normal and low illumination conditions of the FPS task (FPS-N and FPS-L), and both the large and small target sizes of the radar task (Radar-L and Radar-S, respectively) in Table 8. In separate analyses of variance for FPS and Radar tasks, again excluding normals, the main effect of type of deficiency, and the interaction of type with degree were highly significant, as in the analysis of data for the normal FPS task (normal illumination only). In addition, the main effect of illumination was also significant [$F(1,117)=43.67$, $p<.001$], but the factor of illumination did not interact with either type or degree of deficiency; i.e. the detrimental effects of illumination and type of deficiency are additive in the FPS task. An analysis of variance of the Radar-L and Radar-S tasks data of Table 8 indicated only a significant main effect of target size [$F(1,117)=135.65$, $p<.001$], but no other significant main effects or any significant interactions.

CONCLUSIONS

Normal color vision is required for performance of certain tasks by ATCS personnel; i.e. the probability of error is higher in the simulations of safety critical ATCS color tasks for all diagnostic categories of red-green color vision deficiency than for normal trichromats. The present data show that error in simulated ATCS color tasks was rare among normal trichromats in normal operating conditions. The higher probability of error among deficients is evidenced: (1) by the very small number of color deficient individuals who were able to perform all ATCS practical tasks without any error, and (2) in terms of mean number of errors which increases with degree of color vision deficiency. In normal observation conditions, less than 2 percent of normal trichromats made an error on one of the 3 ATC-related tasks, and less than 5 percent of normals made an error on the FSS-related radar task. Many individuals with color vision deficiency made many errors on all tasks under normal conditions. Color vision deficients were also more adversely affected than normal trichromats under marginal illumination conditions in the Flight Strips task and with small targets in the radar task. Therefore, under adverse viewing conditions, including unexpected situations such as workstation lamp failure, etc., the probability of error in color identification or discrimination will still be much lower for normal trichromats than for individuals with color vision deficiency.

As mentioned previously (Mertens, 1990), the occurrence of some errors in normal trichromats observed in the present study under adverse observation conditions in the flight strips and radar tasks is also of concern. Extremely low illumination levels for flight strips should be avoided, and dependence on color discrimination of small-sized radar targets also should be avoided, especially when targets are on the order of 0.1 degree in size. Measures to prevent such marginal conditions should be considered. Three types of color weather radar displays examined by the authors all have a "zoom" function that can be used to enlarge target size. It should be noted that the FAA currently requires "Flight Watch" positions (controllers who brief aircraft in flight) at flight service stations to use a Remote Radar Weather Display System (RRWDS); other types of briefing positions often do not have that equipment. The RRWDS system has level blink and level delete special functions, in addition to the zoom function, which can provide redundant cues in parallel with the color code for weather level. The present findings support the desirability of having and using such special functions in all color weather radar display systems.

Color vision deficients with red-green deficiencies comprise over 99.9% of all inherited color vision deficiencies, and the findings of this study apply only to the screening of those individuals, since the rare blue-yellow (tritan) deficients were not a part of this study. The question should be raised whether ATCS color vision screening should include testing for tritan deficiencies. Because critical ATCS color tasks of the present ATCS environment involve the colors red, yellow, green, and white, it is felt that the impact of tritan deficiencies would be negligible. However, that may not remain the case as increasing use of color-CRT workstations is planned for future ATCS air traffic control and weather information systems. Additional studies are planned to evaluate the color vision requirements of color displays being developed for future ATCS use.

REFERENCES

Adams AJ, Tague MK. Performance of air traffic control tasks by protanopic color defectives. Am. J. Opt. Physiol. Opt. 1985; 62:744-50.

Box GEP. Some theorems on quadratic forms applied in the study of analysis of variance problems. I. Effect of inequality of variance in the one-way classification. Ann. Math. Stat. 1954; 25:290-302.

Illumination Engineering Society. Illumination engineering handbook (5th Ed.). New York: Illumination Engineering Society of New York, 1972.

International Civil Aviation Organization. Airworthiness technical manual. Document 9051-AN/896, Amendment 10. 1000 Sherbrooke Street West, Suite 400, Montreal, Quebec, Canada, November 14, 1988.

Kuyk TK, Veres III JG, Lahey MA, Clark DJ. The ability of protan color defectives to perform color-dependent air traffic control tasks. Amer. J. Optom. Physiol. Optics. 1986; 63:682-6.

Kuyk TK, Veres III JG, Lahey MA, and Clark DJ. Ability of deutan color defectives to perform simulated air traffic control tasks. Amer. J. Optom. Physiol. Optics. 1987; 64:2-10.

Lahey MA, Veres III JG, Kuyk TK, Clark DJ, Smith EN. Job analysis and determination of color vision requirements for air traffic control specialists. Report submitted under Contract OPM-50-83 with the U.S. Office of Personnel Management, (1984 a).

Lahey MA, Kuyk TK, Veres III JG, Clark DJ. The impact of color weather radar equipment on the job of air traffic control specialists - flight service station option. Report submitted under Contract OPM-50-83 with the U.S. Office of Personnel Management, (1984 b).

Mertens HW. Evaluation of functional color vision requirements and current color vision screening tests for air traffic control specialists. Report DOT/FAA/AM-90/9. Washington, DC: Federal Aviation Administration, Office of Aviation Medicine, 1990.

Mertens HW, Milburn NJ. Validity of clinical color vision tests for air traffic control specialists. (in preparation) 1992.

National Research Council-National Academy of Sciences, Committee on Vision. Procedures for testing color vision: Report of working group 41. Washington, DC: National Academy Press, 1981.

Pokorny J, Smith VC, Verriest G, Pinckers AJLG. Congenital and acquired color vision defects. New York: Grune and Stratton, 1979.

Steen JA, Collins WE, Lewis MF. Utility of several clinical tests of color defective vision in predicting daytime and nighttime performance with the aviation signal light gun. Aerospace Med. 1974; 45:467-72.

APPENDIX A

Table 1. Age of Subjects with Normal and Deficient Color Vision in Each Experiment

Experiment		Age (yrs) Normal	Deficient
I	Mean	31.4	27.9
	S.D.	7.4	8.9
	n	37	71
II	Mean	32.3	33.5
	S.D.	9.7	12.4
	n	71	52

Table 2. Sex of Subjects with Normal and Deficient Color Vision in Each Experiment

Experiment	Sex	Classification Normal	Deficient
I	Male	23	67
	Female	14	4
II	Male	65	49
	Female	19	3

Table 3. Anomaloscope Classifications of Subjects in Experiments I and II

Experiment	Normal Trichromat	Anomalous Trichromat				Dichromat	
		Simple		Extreme			
		Prot	Deut	Prot	Deut	Prot	Deut
I	37	4	15	6	15	11	20
II	84	4	8	12	11	7	10
Combined	121	8	23	18	26	18	30

Table 4. Number of Subjects Passing or Failing Four Simulated ATCS Color Tasks as a Function of Color Vision Deficiency

TASK		Normal Trichromat	Anomalous Trichromats: Simple Prot	Simple Deut	Extreme Prot	Extreme Deut	Dichromats: Prot	Deut
1. Flight Progress Strips (59 lux Illumination)	Pass	120	5	8	0	0	0	1
	Fail	1	3	15	18	26	18	29
2. Aircraft Lights	Pass	119	3	6	2	1	0	1
	Fail	2	5	17	16	25	18	29
3. ASL Indicator*	Pass	120	6	15	3	10	1	3
	Fail	0	2	7	15	16	17	27
4. Color Weather Radar (0.5 Deg Targets)	Pass	115	2	17	0	4	0	3
	Fail	6	6	6	18	22	18	27
COMPOSITE SCORES								
ATC Tasks (Fail with any error, Tasks 1-3)	Pass	119	3	4	0	0	0	0
	Fail	2	5	19	17	26	18	30
ATC/FSS Tasks (Fail with any error, Tasks 1-4)	Pass	113	2	4	0	0	0	0
	Fail	8	6	19	18	26	18	30

* ASL data were lost for one Normal and one Simple Deuteranomalous due to technical error.

Table 5. Comparison of Number of Subjects Passing on Composite Scores in Experiments I and II

Composite/ Experiment		Normal Trichromat	Anomalous Trichromat Simple	Anomalous Trichromat Extreme	Dichromat
ATC/FSS TASKS					
I	Pass	36	1	0	0
	Fail	1	18	21	31
II	Pass	77	5	0	0
	Fail	7	7	23	17
ATC TASKS					
I	Pass	37	1	0	0
	Fail	0	18	21	31
II	Pass	82	6	0	0
	Fail	2	6	23	17

Table 6. Number of Subjects Passing or Failing Simulated ATCS Color Tasks as a Function of Color Vision Deficiency and Adverse Viewing Conditions

		COLOR VISION CLASSIFICATION						
		Normal	Anomalous Trichromats				Dichromats	
			Simple		Extreme			
ATC TASKS		Trichromat	Prot	Deut	Prot	Deut	Prot	Deut
Flight Progress Strips								
FPS-N (59 lux Illum.)	Pass	121	6	8	0	4	0	1
	Fail	0	2	15	18	22	18	29
FPS-L (14 lux Illum.)	Pass	117	4	5	0	2	0	1
	Fail	4	4	18	18	24	18	29
FSS TASKS								
Color Weather Radar								
Radar-L	Pass	115	2	17	0	4	0	3
(0.5 Deg Targets)	Fail	6	6	6	18	22	18	27
Radar-S	Pass	84	1	4	0	0	0	0
(0.1 Deg Targets)	Fail	37	7	19	18	26	18	30

Table 7. Errors on the FPS, ALT, and ASL Tasks as a Function of Type and Degree of Color Vision Deficiency in Normal Observation Conditions

TASKS	DIAGNOSIS	MEAN	STANDARD DEVIATION	95% CONF. INTERVAL
Flight Progress Strips	**Normal**	0.01	0.09	-0.01 to 0.02
	Protan			
	Simple	2.63	4.07	-0.78 to 6.03
	Extreme	36.50	22.62	25.25 to 47.75
	Dichromat	48.56	11.70	42.74 to 54.38
	Deutan			
	Simple	5.13	8.01	1.67 to 8.59
	Extreme	11.54	8.64	8.05 to 15.03
	Dichromat	15.03	9.19	11.60 to 18.46
Aircraft Lights Task	**Normal**	0.02	0.20	-0.01 to 0.06
	Protan			
	Simple	1.63	1.76	0.15 to 3.10
	Extreme	6.50	4.03	4.49 to 8.51
	Dichromat	8.61	3.71	6.77 to 10.46
	Deutan			
	Simple	3.22	3.54	1.69 to 4.75
	Extreme	6.39	3.67	4.90 to 7.87
	Dichromat	8.40	3.93	6.93 to 9.87
ASL Indicator	**Normal**	0.00	0.00	0.00 to 0.00
	Protan			
	Simple	0.25	0.46	-0.14 to 0.64
	Extreme	1.39	0.85	0.97 to 1.81
	Dichromat	1.89	0.96	1.41 to 2.37
	Deutan			
	Simple	0.35	0.57	0.10 to 0.60
	Extreme	0.96	0.92	0.59 to 1.33
	Dichromat	1.60	0.89	1.27 to 1.93

Table 8. Errors on the FPS and Radar Tasks as a Function of Type and Degree of Color Vision Deficiency and Both Normal and Difficult Observation Conditions

TASKS	DIAGNOSIS	MEAN	STANDARD DEVIATION	95% CONF. INTERVAL
FLIGHT PROGRESS STRIPS				
FPS-N NORMALS		0.00	0.00	0.00 to 0.00
FPS-N PROTANS	Simple	1.00	1.85	-0.55 to 2.55
	Extreme	12.17	6.74	8.81 to 15.51
	Dichro.	15.44	3.63	13.64 to 17.25
FPS-N DEUTANS	Simple	2.65	3.80	1.01 to 4.29
	Extreme	4.65	4.31	2.91 to 6.39
	Dichro.	8.20	4.87	6.38 to 10.02
FPS-L NORMALS		0.58	0.35	-0.01 to 0.12
FPS-L PROTANS	Simple	3.63	5.13	-0.66 to 7.91
	Extreme	15.00	5.11	12.46 to 17.54
	Dichro.	17.61	2.75	16.25 to 18.98
FPS-L DEUTANS	Simple	4.22	4.63	2.22 to 6.22
	Extreme	6.73	4.36	4.97 to 8.49
	Dichro.	10.57	5.16	8.64 to 12.50
COLOR WEATHER RADAR				
Radar-L NORMALS		0.06	0.27	0.01 to 0.11
Radar-L PROTANS	Simple	1.13	0.99	0.30 to 1.95
	Extreme	2.78	1.48	2.04 to 3.51
	Dichro.	3.56	1.58	2.77 to 4.34
Radar-L DEUTANS	Simple	0.48	0.95	0.07 to 0.89
	Extreme	2.46	2.02	1.64 to 3.28
	Dichro.	3.13	1.80	2.46 to 3.80
Radar-S NORMALS		0.42	0.81	0.28 to 0.57
Radar-S PROTANS	Simple	3.00	1.77	1.52 to 4.48
	Extreme	4.94	2.01	3.94 to 5.95
	Dichro.	5.11	1.61	4.31 to 5.91
Radar-S DEUTANS	Simple	2.22	1.86	1.41 to 3.02
	Extreme	5.12	1.63	4.46 to 5.78
	Dichro.	5.90	2.14	5.10 to 6.70

*U.S. GOVERNMENT PRINTING OFFICE:1992-661-063/60028